How Recent Smart Road Technologies and Construction Materials Can Contribute to the Sustainability of the Road Infrastructure

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Abstract

Rapid worldwide urbanization poses many challenges for the achievement of sustainable cities. The continuous growth in population leads to an increase in resources and services demands which must be addressed together with the rising environmental concerns. The transport sector plays a significant role in enhancing a more sustainable and greener environment which can be achieved with the use of data-driven ICT, innovative technologies and environmentally friendly materials. The use of data-driven ICT and innovative technologies on transport infrastructure are often referred to as smart infrastructures. Among the different smart infrastructures are comprehended the smart roads. Nowadays, an extensive number of smart road solutions exist and are deployed to improve the sustainability of the transport sector and urban areas. This paper presents an overview on smart roads, its components, and on how recent smart road technologies and non-traditional road materials can contribute to the sustainability of the road infrastructure. Finally, this paper discusses the strategies of the Norwegian authorities to enhance a safe and efficient transport sector, in line with the global sustainable development goals.

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1. Introduction:

According to the UN-Department of Economics and Social Affairs (2018), the worldwide population which lives in urban areas is expected to arise from 55.3% (in 2018) to more than 60% by 2030. The number of cities with at least a million inhabitants has been growing from 371 (in 2000) to 548 (in 2018) and by 2030 are expected to reach 706. Still, from 2018 to 2030 megacities (cities with more than 10 million of inhabitants) are expected to increase from 33 to 43. While the urban population is expected to arise, the rural population is expected to decrease from 45% (in 2018) to 40% or even less (in 2030) (UN-Department of Economics and Social Affairs, 2018). This rapid urbanization, and migration from rural to urban areas, leads to a growing demand of resources and services which must be addressed together with the rise of environmental concerns, such as the reduction of CO_2 emissions, air, noise, water pollution, and waste production (Brahmanand Mohanty 2012; Arbabi and Mayfield 2016; Silpa Kaza et al., 2018; OECD 2020). The need to satisfy these demands and, at the same time, lower their environmental impact is, thus, a priority for the sustainable development of urban areas (Council of the European Union 2006; United Nations General Assembly 2015). In this context, the actions to be undertaken to achieve these sustainable development goals include, among others, a responsible consumption and production of energy resources and a more sustainable transport system (United Nations General Assembly, 2015). To satisfy the continuously growing energy and transport demand in a sustainable manner is a complex challenge in which smart cities can be a potential solution. Quoting the International Telecommunication Unition (ITU), smart sustainable city refers to "(…) *an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects*" (United for Smart Sustainable Cities, 2016). Therefore, deploying data-driven Information Communication Technologies (ICT), smart cities enhance a higher quality and efficiency of city services finally improving the relative livability, economic growth, competitiveness and reducing, at the same time, its environmental impact (Hall et al. 2000; Harrison et al. 2010; Caragliu et al., 2013; Yin et al. 2015), and, ultimately, improving its sustainability (Bifulco et al. 2016). Sustainability in cities calls also for sustainability in road transportation (Wadhwa 2000). A sustainable transport system, with relative urban areas, needs an interdisciplinary and integrated approach between transport system, public space, human activities (K. Lu, Han, y Zhou 2018; Yang et al. 2019). However also the use of ICT and innovative technologies can improve the sustainability in the transport sector (Gössling 2018) (Jang et al. 2020).

Transport systems improve the quality of life of its dwellers by promoting the use of properly designed public transport solutions (Boschmann y Kwan 2008; Xia et al. 2017). Each of these solutions have a different impact on how sustainable they are and need to be assessed. To assist decision makers while choosing the most suitable transport solution, (Abdel Warith et al. 2020) build a framework, the Dynamic Index for National Advancements (DINA), to evaluate and compare the sustainable impact of each solutions. Also, McLeod and Curtis (2020) investigated the impact of the inter-relationship between citizen's health, safety and sustainability of the investigated solutions.

The use of ICT in the road transport infrastructure is referred to as smart roads, in academic literature (Zhao y Wu 2015; Sun et al. 2018). Thus, smart road infrastructures are an opportunity to significantly improve road traffic safety, congestion, operations and, simultaneously, optimize the energy resources and its environmental impact (Sun et al. 2018; Trubia et al. 2020; Kamal et al., 2018). The need to collect the already existing works regarding road technologies and environmentally friendly materials is a priority which must be addressed to bring the road transport infrastructure toward more sustainable paths.

This article presents an overview of the recent insights on the smart roads and environmental road materials to improve the sustainability of a road infrastructure. After presenting the smart roads and the state of the art related to them, this article focuses on the materials which can be used to reduce the environmental impact of a road infrastructure and discusses the Norwegian strategies for the enhancement of a more sustainable road transport system. Norwegian authorities, within their *National Transport Plan 2022-2033* (Det Kongelege Samferdeselsdepartement 2021) and the *National Climate Plan 2021-2030* (Det Kongelege Klima Og Miljodepartement 2021) are promoting the construction, planning and design of a safe, efficient, and environmentally friendly transport systems in line with the global sustainable development goals.

2. The Background of Smart Roads

Data-driven ICT can improve the development of sustainable cities by improving the sustainability in transport infrastructure and in transport system (Puodziukas, Svarpliene, y Braga 2016; Gössling 2018; Bamwesigye y Hlavackova 2019). According to the definition of (Zhao & Wu, 2015) "*Smart road is an informational zed road which, on the basis of satisfying basic traffic operation, aim to provide innovative service that contains self-aware, self-adapt, information interaction, and energy harvesting*" (Zhao and Wu 2015). Together with defining what a smart road is, Zhao & Wu (2015) define four functionalities of the smart road each of which can be sub classified in specific tasks. Here are described the four functionalities and subsequent classification according to the same authors (Zhao & Wu, 2015):

- Self-aware: Real-time and automatic evaluation of the road's health condition. The self-awareness function of the smart road is subsequently categorized in four sub-functions based on the monitoring interest from the road practitioners: self-aware of pavement quality (surface, structure and performance), self-aware of road infrastructure, at base and sub-base levels (basic and structure conditions), self-aware of slopes, self-aware of traffic volume conditions.
- Self-adapt: Automatic adaptation of the road to different scenarios, e.g. road condition and road weather. The self-adapting function comprise the following subtasks: road maintenance operations without external assistance, self-melting of snow/ice, self-drain of pavement-water, self-temperature control (to avoid too high or too low temperature) self-clean (e.g. absorb road contaminants) and self-traffic-adjustments.

- Information interaction: the ability to exchange information, thus communicate, between data-driven ICT of road users, smart roads and road authorities and road practitioners. More details are available in section three of this work.
- Energy harvesting: the ability of the road to collect and utilize energy from the environment. More details are available in section four of this work.

Following the definition of smart roads and its functionalities provided by Zhao and Wu 2015, Pompigna y Mauro 2021 envision the smart road as a system in which each functionality has to cooperate and work synergistically to the successful and efficient deployment of the smart road system from the road users. Nowadays, there are an extensive number of projects worldwide related to smart road infrastructures. The recent reviews from Toh et al. (2020); Trubia et al. (2020); Hashem and Cardino (2020) present the latest advancements related to these innovative projects focused on smart roads.

According to Toh et al. (2020) there are ten technologies which enhance the roads to: harvest and store energy, charge electric vehicles, statically and dynamically weigh vehicles, generate music; improve traffic violation controls, improve rescuing operations, enable communication between road users, infrastructure, and road practitioners. Also, Trubia et al. (2020) describes smart road environments as able to collect and store energy, monitor traffic and road conditions, and enable communication between road users, the infrastructure, and practitioners. In this line, Hashem and Cardino (2020) focus their work on how smart roads can harvest and store energy and be smartly maintained using mobile phones. In fact, smartphone applications can alert road authorities, leading to prompt maintenance action if required.

These innovations, according to their authors (Trubia et al. 2020; Toh et al. 2020; Hashem y Cardino 2020), improve, in different manners, the road environment and its related traffic conditions. For instance, roads can be adapted to produce clean energy that can be later used to power electric vehicles, road furniture (e.g., road lights and the electric grid), therefore facilitating the transition to a more sustainable use of the roads. Technologies as smart traffic signs and speed controls can improve traffic safety by focusing the attention of the driver and improving the comfort and perception of the road and relative surroundings while driving. Among the benefits of such technologies, Trubia et al. (2020) also highlight the ease of drivability for autonomous vehicles on smart road infrastructures.

3. The Intelligent Transportation System (ITS) and Communication Protocols in Smart Roads:

With the use of ICT, the Intelligent Transport System (ITS) is an essential part of smart road infrastructure. The adoption of ITS provides a wealth of information in traffic, road conditions, and weather forecasts (Setoshita et al. 2020; Losurdo et al. 2017). ITS, based on mobile and fixed sensors, generates information through data. The integration of such data sources, together with appropriate data management tools, can improve the quality of the information regarding the monitoring of the road network in (smart) road environments (Finogeev et al. 2019; El-Wakeel et al. 2018; Giudici et al., 2021). With a focus on winter conditions, Shi (2020) reviews infrastructure communication technologies, namely Connected Infrastructure (CI), which can improve the road maintenance activities and traffic management. With the aim of improving the monitoring of road deterioration, (Lenglet et al., 2017) presents how embedded sensors, integrated in the pavement layers, can provide information regarding early states of damage before appearing on the road's surface, highlighting that this approach might improve the road maintenance operations and traffic safety. Similarly, Toh et al. (2020) reviews how sensors integrated in the pavement are deployed to weigh heavy trucks in a static and dynamic manner on highways.

The components of a smart road environment are connected in a way that enhances the exchange of information between vehicles and “everything”, such as the infrastructure, vulnerable road users (e.g., pedestrians, cyclists), and road maintenance personnel through the data cloud (Ullah et al. 2019). The exchange of information between the vehicle and these smart road “elements” relies, among other aspects, on the advanced development of communication technologies. Indeed, the advancements in network communication, such as 5G, provide easier accessibility to the generated information while ensuring a high flow of data communication at high reliability and low latency (Bennis et al., 2018; Molinaro and Campolo 2019). Consequently, continuous real-time exchange of information between vehicles to everything (V2X), infrastructure (V2I), vehicles (V2V), pedestrians (V2P), the cloud (V2C), and other sources is provided (Ullah et al. 2019). Toh et al. (2020) shows multiple cases where such communication improves traffic safety, e.g. vehicles (autonomous or not) that communicate with traffic signs. In fact, wireless digital traffic signs with designed servers can be programmed to send information to oncoming vehicles. Thus, drivers are alerted without losing their focus while driving, which enhances traffic safety. Also, digital traffic signs can communicate with Autonomous Driving Assistance Systems (ADAS) of vehicles in case of traffic violations, ameliorating the speed control of road users while driving (Figure 1).

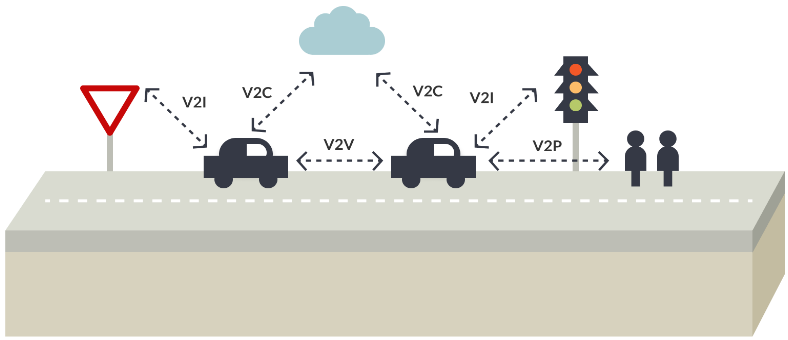

Figure 1. Scheme of communication protocols (modified from Toh et al., 2020)

Therefore, vehicles play a major role in capturing, processing, and sending information regarding the road infrastructure to other road users. Vehicle's ADAS systems can significantly support the human drivers to a point where they can take control of the vehicle, if needed. Thanks to these advanced ADAS systems and the way in which they are able to perceive the road, AV are recognized to be "new road users" according to Storsæter, Pitera, and McCormack 2020. Due to their ability of understand, adapt, and communicate, AVs and CVs are fundamentals for the development of smart road systems to a point where sometimes both terms, CVs and smart roads, are adopted interchangeably (Pompigna y Mauro 2021). The importance of the CV is also supported by Guerrieri 2021, which pictures in the deployment of CVs, AVs, CAVs in the smart road system, a better efficiency of traffic volume and increased traffic safety. This author suggests that the geometric design of the road infrastructure has to be adapted to the CAVs to facilitate the performance of these "new road users" establishing therefore a correlation between the smart geometric road design and road capacity of the CAVs. Also, Storsæter, Pitera, and McCormack 2020, describe that traditional road design and maintenance strategies have to be adapted the needs of AVs and defining how poor road conditions/road furniture (presence of road defects, poor quality of road markings, traffic signs, etc.) might challenge the AVs perception and therefore their deployment.

Therefore, in agreement with the mentioned authors, the accomplishment of the AVs, CVs, CAVs is strongly depended on the satisfactory condition of the smart road system and on its smart geometric design, road maintenance and on the smart road construction which needs to come closer to these new road users satisfying also their needs. However, although the challenges, AVs, CVs, CAVs are recognized to have high potentialities to improve the efficiency in road traffic, reducing accidents, lower vehicle exhaust production, thus, reducing the environmental impact of road transport and at the same time be more energy friendly (Chehri y Mouftah 2019). Especially the latter aspect is a major priority to enhance the continuously efficient functioning of the smart road infrastructure's digital solutions.

4. Harvesting Energy from Smart Roads:

Roads can harvest energy which can be used as a clean power supply for different purposes such as charging electric vehicles in motion, digital traffic signs and road lights (Toh et al. 2020), or melting ice and compacted snow layers (Faisal et al., 2016). Nowadays, there are several methodologies which can be deployed to harvest and store energy from roads including energy generation from the sun (solar roads), by mechanical vehicle movement (piezoelectric roads), and by thermoelectric power.

Solar roads refer to modular panels located on the top of the pavement surface which capture solar energy, convert it to electricity using photovoltaic cells, and transmit it to collectors which store and re-use the harvested energy (Luque and Hegedus 2003). The panels can be used as stand-alone devices or in grid-connection installations. The former requires a storage unit while the latter does not necessitate it (Luque and Hegedus 2003).

The panel's design, structure, and properties influence its performance (Northmore 2014) and, for this reason, its design is under ongoing studies to improve its storage capability. This technology-based panel is acknowledged to be able to sustain structural and environmental conditions such as applied traffic loads, freezing-thawing cycles, and road salting. In addition, these modular panels are easily replaceable, facilitating easier pavement maintenance (Luque and Hegedus 2003; Northmore 2014; Hashem and Cardino 2020). Although the challenges to be solved regarding the captured energy's optimization and storage are numerous, this technology has high potential to produce clean energy, resulting in a positive environmental impact (Luque and Hegedus 2003; Northmore 2014; Settou et al. 2019).

Piezoelectric roads refer to piezoelectric elements, such as crystals, located underneath road surfaces which can collect kinetic energy produced by mechanical actions from vehicles and pedestrians. While moving over the pavement surface, the vehicle applies pressure to the piezoelectric elements converting this mechanical action to electrical energy. Although this emerging technology is a promising method of energy production from roads, it also faces challenges regarding the density of the harvested energy or appropriate storage energy methods (Duarte et al. 2013; Hill, Agarwal, y Tong 2014; Caliò et al. 2014).

Thermoelectric power can be generated wherever a temperature differential is found. In pavements, thermoelectric power can be produced from the natural temperature difference between pavement layers. This power can be used to operate any electrical unit, from light bulbs to electric cars. However, the Thermoelectric Generators (TEG) that are currently available cannot yet produce a large amount of electricity. For this reason, the applications proposed in this paper are not still energy intensive (Zhu et al., 2019; Shaaban, Abdel-Warith, and Haddock 2019).

Finally, to summarize the methods explained in this section regarding the energy source roads, a schematic illustration (Figure 2), based on the concepts proposed by Shi, (2020) and Wang et al., (2018) is shown.

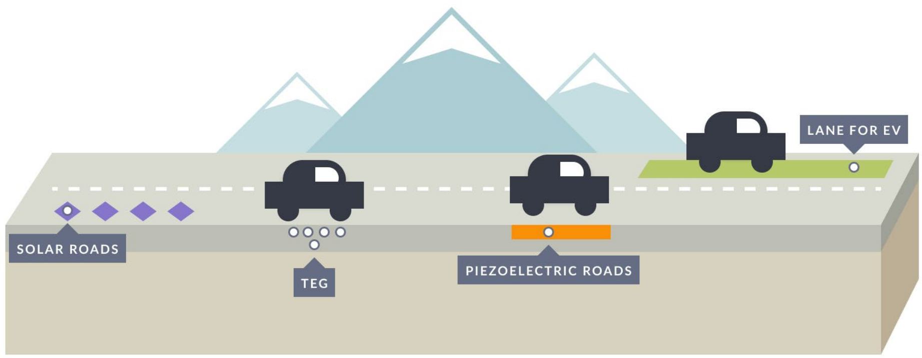

Figure 2. Smart roads energy harvesting (modified from Wang et al., 2018 and Shi 2020).

5. Non-Conventional Environmental Road Material:

The use of environmentally friendly materials reduces the impact of new paved roads improving thus their sustainability. Environmentally friendly materials can be used for paving roads' surfaces to reduce the negative environmental impact caused by the actual construction methods. Conventional alternatives, such as Recycled Asphalt Pavement (RAP) has been extensively investigated during the last decades by researchers and engineers. Thus, this section focuses on the use of environmentally friendly materials designed and produced in recent years.

The use of recycled tire rubber in pavement construction (e.g., modified asphalt and concrete mixture) and pavement furniture (e.g., speed bumps) gained high attention from research to road practitioners due to its high sustainable potentiality (Shu y Huang 2014). Recycled rubber, when mixed with asphalt, leads to a better performance in terms of pavement distress and resistance to temperature variations, thus improving pavement durability (Shu and Huang 2014; Mashaan et al. 2012; Cao 2007; Tortum et al., 2005). Self-illuminated roads using luminescent cement-based pavement (e.g., phosphor-based material) can be used to reduce both light pollution and energy consumption (Wang et al. 2021). These materials are capable of substituting part or all of the external lighting source on roads, being also a promising technology to solve traffic safety problems caused by sudden power outages on roadways, irregular illumination, or drivers' visual fatigue caused by the glare of traditional street lighting (Gao et al. 2018; Wang et al. 2021). The land transport sector is the largest producer of air pollutants, such as NO_x and primary particle matters, mostly emitted by vehicles (Huertas Cardozo y Prato Sánchez 2019), causing several negative health outcomes to inhabitants near roads, especially in big urban areas (Cordero et al. 2020). In this context, researchers, stakeholders, and public administrations are trying to implement photocatalytic pavements, which consist of a surface layer of titanium dioxide (TiO_2) nanoparticles, that can reduce or oxidize both organic and inorganic particles when irradiated by UV light, therefore mineralizing most of the harmful contaminants (Beeldens 2006; Asadi et al. 2014). Although these materials are a promising solution to remove air pollutants in urban areas, this technique is limited by several variables, such as the environment surrounding the roads like relative humidity or UV intensity, complicating the monitoring and interpretation of laboratory and field test results (Asadi et al. 2014; Cordero et al. 2020). For instance, the TiO_2 nanoparticles are progressively removed from the surface of the pavement due to loss of adherence by the effect of traffic, and environments with a higher relative humidity lower the effectiveness of these materials, limiting their use to dry climate areas and to a short-term use (Hingorani et al. 2020).

As it has been mentioned in previous sections, pavement mixtures are able to absorb and store solar energy during the daytime. This energy is then released at night, increasing the environment's temperature and generating the so-called urban heat islands, which have a negative impact on the thermal comfort and health of urban populations, especially during heat waves (Heaviside et al., 2017). Equally, these pavement mixtures are impermeable systems that modify the hydrological characteristics of roads environment and, for instance, the natural ecology of the constructed area (Lu et al. 2020; Scholz and Grabowiecki 2007; Tennis et al., 2004). Therefore, to reduce the negative impact of road pavements in the heat exchange between the natural soil interface, the atmosphere, and the rainwater system, pervious pavements are beginning to replace traditional pavement mixtures (Tan et al. 2021; Liu et al. 2020). These pavements are open porous structures capable of accumulating, infiltrating, and purifying natural storm and rainwater and mitigating the urban heat island via evaporative cooling in hot-humid regions (Liu et al. 2020; Mullaney y Lucke 2014).

Asphalt materials possess the self-healing capability for repairing microcrack damages, which can restore its functionality at least to some extent and considerably reduce maintenance costs, as well as extend its service life and eventually decrease the emission of greenhouse gases (Sun et al. 2018). Equally, in recent years, self-healing concrete that is based on the use of bacteria (bio-concrete) is becoming more important to improve the durability of buildings and structures, especially bridges and roads. The main mechanism of bacterial concrete crack healing is that the bacteria itself acts largely as a catalyst and transforms a precursor compound to a suitable filler material. The newly produced compounds, such as calcium carbonate-based minerals, precipitates as a type of bio-cement which effectively seals newly formed cracks (Jonkers 2011).

Recycled plastics can be adopted in different forms to improve the performance and life service of the paved road, reducing the negative environmental impact of road infrastructure and at the same time recycle the plastic waste (Gawande et al. 2012; Chavan 2013; S. Yin et al. 2015; Hashem y Cardino 2020; Trubia et al. 2020). Recycled plastic can be deployed as road construction material mixed with concrete, bitumen and also in form of prefabricated panels (Gawande et al. 2012; Yin et al. 2015; Hashem y Cardino 2020) . Recycled plastics as polypropylene (PP), (HDPE) and polyethylene terephthalate (PET) can reinforce concrete according to the review of Yin et al. 2015. In the same work, the authors highlight the benefit in the mechanical properties of the concrete if mixed with macro plastics fibres as: improved performance of plastic shrinkage, ductility, flexural resistance, and energy absorbance. The performance of bitumen mixture with plastic additives in controlled conditions in investigated by Gawande et al. 2012 which conclude that the investigated mixture have better performance in stability, fatigue, and strength together with water resistance. Their laboratory results were validated in two different test sites showing reasonable degree of agreement between indoor and outdoor performance. Plastic can be also used in form of prefabricated panels to build roads, according to Trubia et al. (2020) and Hashem and Cardino (2020). According to the authors, the use of these panels can improve the rapidity of the building process, make easier the relative maintenance.

6. Discussion:

This paper presents the use of technologies and environmentally friendly materials for the enhancement of a more sustainable road transport sector. To achieve the sustainable development of road transport, different countries have adopted different strategies. In this paper are discussed the Norwegian strategies toward a more sustainable road transport sector. Norwegian authorities released their strategies in the *National Transport Plan 2022-2033* (Det Kongelege Samferdeselsdepartement 2021) and the *National Climate Plan 2021-2030* (Det Kongelege Klima Og Miljodepartement 2021) which are characterized by ambitious sustainable and environmental goals and the pervasive use of technologies to achieve them. The *Norwegian Climate Plan* (Det Kongelege Klima Og Miljodepartement 2021) aims to reduce 45% of CO_2 emissions production by 2030. The long-term objective of the Det Kongelege Samferdeselsdepartement (2021) is to build a safe, efficient, and environmentally friendly transport system by 2050. These strategies come along with a wealth of other objectives such as the significant reduction of mortal or severe injured accidents on roads, an improved performance of road transport (e.g., transport time, road traffic, etc.), and the reduction of air, noise and microplastics pollution. According to both Det Kongelege Klima Og Miljodepartement (2021) and Det Kongelege Samferdeselsdepartement (2021), the Norwegian authorities established a framework of facilitations composed by significant financial investments and a wealth of laws and regulations aiming to: i) develop technologies based on innovation; ii) strengthen the cooperation between the industry and research environments; iii) facilitate the different phases (development, implementation, piloting, operation) of technological solutions; iv) facilitate the use of data-driven technologies.

Transport automation, electrification, zero emission mobility, smart mobility, quoting (Det Kongelege Samferdeselsdepartement 2021) "*in themselves also represent new solutions to known problems*". Despite the high potentialities, there are still open challenges to overcome prior to full deployment of these technologies on roads in a sustainable manner. In this regard Shi (2020) envisages the research needs in the CI, such as the optimized performance and design, of harvesting energy road solutions and a better integration between the road infrastructure and ICT. With respect to the automation in road transport, Storsæter, Pitera, and McCormack (2020) define the concept of automated driver as a new road user, suggesting the implementation of these automated road users in the design and maintenance of roads as possible research directions. Equally, the design, construction, and rehabilitation of the infrastructure is known to have an impact on the transport sector's sustainability (Det Kongelege Klima Og Miljodepartement 2021). In this regard, environmentally friendly materials can improve the sustainability of the road infrastructure.

Road transport performance and its sustainable impact are also influenced by the maintenance phase (Montoya-Alcaraz et al., 2020). This is true also in winter where the relative maintenance actions, such as road salting and snow removal, have an impact on the road's sustainability. The former by spreading excessive salt on roads that is harmful to the environment, and the latter by producing excessive CO_2 due to the continuous driving action of snow removal vehicles (Det Kongelege Samferdeselsdepartement 2021). Recent research activities show that road salting can be reduced without compromising traffic safety (Giudici et al., 2019; Giudici et al., 2020). However, to the knowledge of the authors, the optimization of snow removal actions still requires attention to prevent the accelerated deterioration of pavements surfaces (Pérez Fortes et al. 2016; Pérez-Fortes, Varas-Muriel, y Castiñeiras 2017; 2021).

7. Conclusions:

This paper presents an overview of recent insights on the use of technologies and environmentally friendly materials for the enhancement of a more sustainable transport sector. The urgent call of sustainability has become a priority where smart roads offer an opportunity to improve the sustainability of the road transport sector. Nowadays more than ever, smart technologies and environmentally friendly materials can improve the sustainability of a road infrastructure and, at the same time, their performances, although important challenges still must be resolved. Finally, we would like to conclude this review with some words from the Norwegian National Transport Plan (Meldt. St. 20, 2021): "*A more sustainable transport sector can be done with the co-joint use of technological advancements and daring to think in a new way*".

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